Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 45, No. 1 (2015), 29 – 38

The parameter estimation of the electrothermal model of inductors

Krzysztof Górecki, Kalina Detka

Gdynia Maritime University, Department of Marine Electronics, Gdynia, Poland

Abstract: This paper presents the electrothermal model of inductors dedicated to the analysis of dc-dc converters in SPICE and the proposed method of determining parameters of this model. The parameter estimation algorithm of this model is described in detail. The results of verification of the correctness of the model and the estimation procedure for arbitrarily selected choking - coils are presented. Very good agreement between the calculated and measured characteristics of the considered choking-coils was obtained.

Keywords: Inductors; modelling; parameters estimation; self-heating

Ocena parametrov elektrotermičnega modela tuljav

Izvleček: Članek opisuje elektrotermični model in določevanje parametrov tuljav, ki se uporabljajo v dc-dc konverterjih v SPICE. Natančno je opisan algoritem določevanja parametrov modela. Predstavljeni so rezultati verifikacije modela in postopek ocenitve parametrov na izbranih tuljavah. Rezultati simulacij se dobro ujemajo z meritvami.

Ključne besede: Tuljava; modeliranje; ocean parametrov; samogretje

** Corresponding Author's e-mail: gorecki@am.gdynia.pl*

1 Introduction

Inductors are important components of switched-mode power converters [1 - 4]. Properties of such converters depend on the properties of their structural components, i.e. the ferromagnetic core and the winding. Ferromagnetic materials used to build the core of the inductor are characterized by magnetization hysteresis characteristics. The magnetic permeability of the core, which is proportional to the inductance of inductors is a non-linear function of magnetic force and temperature [5 - 11].

In designing electronic circuits the computer programs dedicated to their analysis are used. Currently, one of most popular programs for this analysis is SPICE software [12 – 15]. The credibility of calculation results depends on the accuracy of the models of the used elements [16]. The inductor models typically use a linear model of the coil or non-linear model of the core and the linear model of the winding [2, 13, 17]. Nonlinear models of the core were presented in [3, 10, 13, 18, 19], but various modifications of the Jiles–Atherton model are the most commonly used models [6, 7, 11, 18, 19, 20]. This model does not take into account such an important phenomenon as self-heating.

In papers [3, 18] the electrothermal model of the chocking-coil for SPICE using the electrothermal core model presented in [11] is proposed. The electrothermal model of the choking–coil is devoted to calculate parameters of its model for the inductor used in the analyzed circuit. Therefore, it is important to prepare algorithm parameter estimation of such a model. This paper presents a modified form of the electrothermal model of the inductor, proposes the method for determining parameters of the model and provides an example of the results of calculations and measurements to illustrate the correctness of the elaborated method.

2 The electrothermal model of the inductor

The presented electrothermal model of the choking – coil takes into account electrical phenomena occurring in the winding, magnetic phenomena occurring in the core and thermal phenomena in the core and the winding. Due to the fact that the choking – coil core is made of soft magnetic material the hysteresis of the magnetization curve can be omitted in the model [6]. The considered electrothermal model of the choking - coil has the form of a sub-circuit of SPICE. The network representation of the elaborated model is presented in Figure 1. The model is composed of three blocks. The first block is the main circuit and it includes a series connection of controlled voltage sources E_{LS}, E_{RS}, the voltage source V_L with the zero value and the coil with inductance L equal to 2 µ H and the parallelly connected capacitor C_w modeling interturn capacitance of the winding.

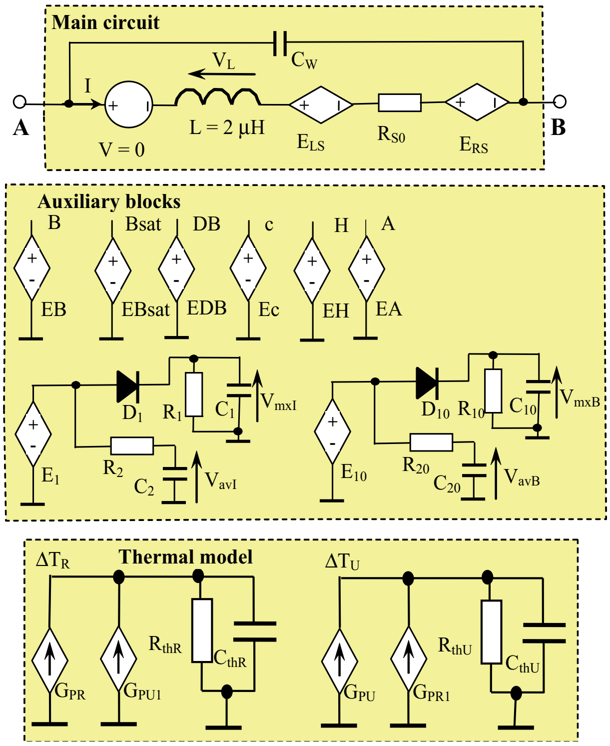


Figure 1: Network representation of the electrothermal model of the inductor

The voltage source V_L monitors the value of the current of the choking – coil. The coil L make it possible to calculate the time derivative of the current of the choking – coil. E_{LS} represents the voltage drop on non-linear inductance of the choking – coil and is described by the formula [3]

$$E_{LS} = w_S \cdot \frac{f \cdot V_L}{(f + f_b) \cdot L} \cdot L_S = w_S \cdot \frac{f \cdot V_L}{(f + f_b) \cdot L} \cdot \frac{z^2 \cdot S_{Fe} \cdot B_{sat} \cdot A}{l_{Fe} \cdot \left(|H| + A\right)^2 + A \cdot B_{sat} \cdot l_p / \mu_0} \quad (1)$$

where z denotes the number of turns in the choking–coil winding, V_L - voltage on the coil L, S_{Fe} - effective cross-section area of the core, B_{sat} – saturation magnetic flux density, H - magnetic force in the core, l_{Fe} - magnetic path in the core, A – the field parameter, l_p - air gap length in the core, μ_0 – permeability of free air, which amounts to 12.57 • 10^{-7} H/m, dB/dH – magnetic permeability of the core, f – the frequency of the inductor current, f_b - reference frequency.

The resistor R_{SO} represents series resistance of the inductor at temperature T_0. The value of this resistance is described by formula:

$$R_{SO} = \rho \cdot \frac{l_d}{S_d} \quad (2)$$

where ρ is resistivity of copper equal to 1.72 • 10^{-8} Ω•m at temperature 20° C, l_d is the length of winding, and S_d is the cross-section of the coil wire.

In turn, the controlled voltage source E_{RS} is described by:

$$E_{RS} = V_{RS} \cdot \alpha_\rho \cdot \left(T_U - T_0\right) + \frac{l}{d} \cdot \sqrt{\mu_0 \cdot \rho \cdot \left(1 + \alpha_\rho \cdot \left(T_U - T_0\right)\right)} \cdot 2 \cdot \left(I - I_{av}\right) \cdot$$
$$\cdot \sum_{n=1}^{4} \sqrt{n \cdot f} \cdot \left(a_n \cdot \cos\left(\frac{2 \cdot \pi \cdot f}{t}\right) + b_n \cdot \sin\left(\frac{2 \cdot \pi \cdot f}{t}\right)\right) + P_R \cdot \frac{I}{I_{sk}^2} \quad (3)$$

In the equation (3) there are three components. The first one models the dependence of series resistance on temperature. The V_{RS} is a component of the voltage across the resistor R_{SO}, α_ρ is the temperature coefficient of resistivity of copper, which amounts to 4.45 • 10^{-3} K^{-1} and T_U is temperature of the winding. The second component models the additional voltage drop at the choking–coil which is a result of the skin effect. To describe these phenomena one takes into account the fact that the current of the choking–coil operating in the dc-dc converter has a periodic triangular waveform. This waveform is modeled with a Fourier series, wherein the number of components is limited to four. The Fourier series coefficients of the model are described by:

$$a_n = \frac{2 \cdot \cos\left(2 \cdot n \cdot \pi \cdot (d_1 - 0{,}5) - (-1)^n\right)}{d_1 \cdot n^2 \cdot \pi^2 \cdot \left(1 - d_1\right)} \quad (4)$$

$$b_n = \frac{\sin(2 \cdot n \cdot \pi \cdot (d_1 - 0{,}5) - (-1)^n}{2 \cdot \pi^2 \cdot n^2 \cdot d_1 \cdot (1 - d_1)} \quad (5)$$

where I is choking–coil current, d – diameter of the coil wire, I_{av} – average value of the coil current calculated in the auxiliary block, d_1 - duty of the converter control signal, and f – frequency of this signal. The third component in the formula (3) represents the choking–coil voltage drop resulting from energy losses in the core. The P_R component describe energy losses in the core, I_{sk} is the RMS value of the choking–coil current.

In the auxiliary block the following are determined: magnetic force *H*, magnetic flux density *B*, the time derivative of the magnetic flux density *DB*, field parameter *A*, maximum and average values of the magnetic flux density and of the current, coefficient *c* defining the influence of the Curie temperature T_C on the value of the magnetic flux density. Inductance of the inductor is proportional to the magnetic permeability of the core corresponding to the characteristics *B(H)* slope [2, 6, 13]. To determine the value of the magnetic flux density the formula described in [6, 21] is used:

$$B = B_{sat} \cdot \frac{H}{|H| + A} \tag{6}$$

where B_{sat} is the saturation flux density of the core.

On the other hand, the value of the magnetic force is calculated by the formula [5]:

$$H = \frac{z \cdot I - \dfrac{B \cdot l_p}{\mu_0}}{l_{Fe} + l_p} \tag{7}$$

In the auxiliary block, the field parameter *A*, which makes it possible to take into account the influence of temperature on the magnetization curve and inductance of the inductor, is also determined. The dependence of the parameter *A* on temperature is described by the empirical formula:

$$A = A_0 \cdot \exp\left[\left(-T_R + T_a\right)/\alpha_T\right] \tag{8}$$

where α_T is the temperature coefficient of the parameter *A*.

It should be noted that the saturation flux density in the core also strongly depends on temperature and the inclusion of this impact has been expressed by the dependence [6, 10, 11]:

$$B_{sat} = B_{sat0} \cdot \left[1 + \alpha_{BS} \cdot \left(T_R - T_0\right)\right] \cdot c \tag{9}$$

where B_{sat0} is the saturation flux density at temperature T_0 and α_{BS} – the temperature coefficient of B_{sat}.

The *c* coefficient was defined by:

$$c = \begin{cases} 1 \quad for\ T_R < T_C \\ 1 - 0.1 \cdot \left(T_R - T_C\right) \quad for\ T_R < T_C + 10K \\ 0 \quad for\ T_R > T_C + 10K \end{cases} \tag{10}$$

where T_R denotes temperature of the core.

On the other hand, to calculate the average and peak-to-peak values of the current, and the magnetic flux density, two detectors are defined: the peak-to-peak value detector and the average value detector, consisting of the two-terminal networks R_1C_1, R_2C_2 and $R_{11}C_{11}$, $R_{21}C_{21}$, diodes D_1 and D_{11}, the controlled voltage sources E_1 and E_{11}, respectively representing the inductor current and the magnetic flux density of the core.

The thermal model is used to determine the core temperature T_R and the winding temperature T_U of the inductor using the compact model proposed in [6, 12, 16, 22 , 23]. This model includes two controlled current sources, representing power losses in the core G_{PR} and in the winding G_{PU}, respectively. The included in this two-terminal circuits R_{thR}, C_{thR} and R_{thU}, C_{thU} represent thermal time constants of the core and the winding, so that it is possible to take into account the phenomena of self-heating. These time constants fulfill equations describing the relation between the controlled current sources and G_{PU1} used for modeling the thermal coupling between the core and winding. The currents of these sources are respectively 0.8 G_{PR} and 0.8 G_{PU}. Depending how one defines a power loss in the winding, G_{PU} includes resistive losses and the skin effect . The losses in the winding are described by the formula:

$$\begin{aligned} P_U = {} & \rho \cdot I^2 \cdot \left[1 + \alpha_\rho \cdot \left(T_U - T_0\right)\right] + l/d \cdot \sqrt{\mu_0 \cdot \rho \cdot f \cdot \left(1 + \alpha_\rho \cdot \left(T_U - T_0\right)\right)} \cdot 2 \cdot \\ & \sum_{n=1}^{4} \sqrt{n \cdot f} \cdot \left(a_n \cdot \cos\left(\frac{2 \cdot \pi \cdot f}{t}\right) + b_n \cdot \sin\left(\frac{2 \cdot \pi \cdot f}{t}\right)\right) \cdot \left(I_{mx} - I_{av}\right)^2 \end{aligned} \tag{11}$$

where I_{mx} is the maximum coil current calculated in the auxiliary block.

In turn, the core losses are described by [10]:

$$P_R = V_e \cdot \left(\frac{DB}{2}\right)^{\beta - \alpha} \cdot \left(1 + D \cdot \left(T_R - T_m\right)\right)^2 \cdot \frac{P_{V0}}{T} \cdot \int_0^T \left|\frac{dB}{dt}\right|^\alpha dt \tag{12}$$

where V_e denotes the equivalent volume of the core, P_{V0} are volumial power losses in the core, *DB* is the magnitude of flux density, *D* – the square temperature coefficient of power losses P_{v0}, *T* - period of a inductor current, *α* and *β* are exponents in the dependence of core losses based on frequency and amplitude of the flux density in the choking–coil, respectively, T_m is the temperature, at which losses are minimal.

3 Parameter estimation

The presented model is described by 20 parameters that can be divided into 3 groups:

a. electrical parameters,
b. magnetic parameters,
c. thermal parameters.

The proposed estimation algorithm uses the concept of local estimation described in [22, 24]. According to this concept, the model parameters are estimated in groups on the basis of the measured characteristics of the inductor operating in specific conditions.

The magnetic parameters of the choking–coil corresponding to the ferromagnetic core reactor can be divided into three groups:

- The parameters of ferromagnetic material, of which the core is made, related to the hysteresis loop, such as the saturation flux density B_{sat0}, the Curie temperature T_C, the field parameter A, the air gap length l_p, the temperature coefficient of saturation flux density changes α_{BS}, the temperature coefficient α_T of the magnetic field parameter,
- The geometric parameters of the core, such as the magnetic path length in the core l_{Fe}, the equivalent value of the core volume V_e, the effective cross-section area of the core S_{Fe},
- The ferromagnetic material parameters corresponding to core losses such as P_{V0}, D, α, β .

Some parameters associated with the magnetic material used to construct the ferromagnetic core can be read directly from the catalog data supplied by manufacturers e.g. the saturation flux density B_{sat0} and the Curie temperature T_C [22].

In order to determine the temperature coefficient of saturation flux density changes the designer needs to:

1. Read from the catalog characteristics , eg, [25, 26], the value of the saturation flux density B_{sat0} at the reference temperature T_0 and the value of this parameter B_{sat1} at a different temperature T_1.
2. Calculate the value of the temperature coefficient of saturation flux density changes according to the formula [22] :

$$\alpha_{BS} = \frac{B_{sat1} / B_{sat0} - 1}{T_1 - T_0} \tag{13}$$

The geometric parameters of the cores should be read from the catalog data or should be determined basis of the dimensions of the core and calculated using the basic geometrical relationships. For example, to determine the geometrical parameters of the ring core one should:

1. determine the dimensions of the core (Fig. 2), i.e. the outer diameter d_z, the inner diameter d_w and height h_R (these data are usually contained in the name of the core, e.g. RTP 26,9 x14, 5x11)

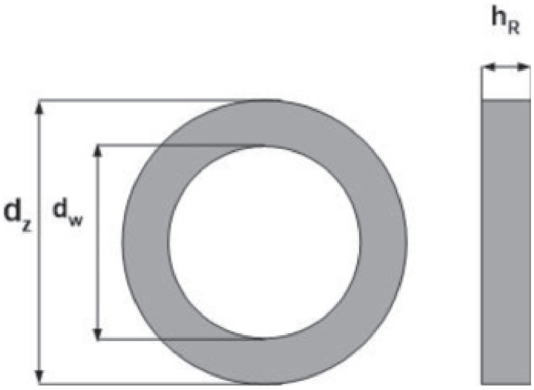


Figure 2: Dimensions of the ring core

2. calculate the magnetic path length in the core l_{Fe} using the formula

$$l_{Fe} = \pi/2 \cdot (d_z + d_w) \tag{14}$$

3. calculate the effective cross-section area of the core S_{Fe} using the formula:

$$S_{Fe} = \frac{(d_z - d_w) \cdot h_R}{2} \tag{15}$$

4. calculate the equivalent value of the core volume V_e by:

$$V_e = \frac{\pi \cdot (d_z^2 - d_w^2) \cdot h_R}{4} \tag{16}$$

In order to determine the values of the parameters A, w_s, and l_p it is necessary to measure the dependence of inductance L on the DC current using the measurement system described in [27]. The measurement should be performed at the frequency $f << f_b$. In the measured characteristics of $L(i)$, whose typical course is shown in Figure 3 one should select 3 points: $X_1(I_1, L_1)$, $X_2(I_2, L_2)$ and $X_3(I_3, L_3)$. Then, the following system of equations must be solved for w_S, l_p and A:

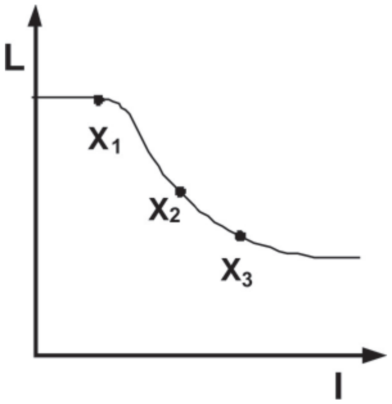


Figure 3: Typical course of the dependence of inductance of the inductor on the dc part of its current

$$\begin{cases} L_1 = \dfrac{w_S \cdot z^2 \cdot S_{Fe} \cdot B_{sat} \cdot A}{l_{Fe} \cdot \left(\dfrac{z \cdot I_1 - B_{sat} - A \cdot x + \sqrt{B_{sat}^2 + z^2 \cdot I_1^2 + A^2 \cdot x^2 + 2 \cdot A \cdot x \cdot (B_{sat} + z \cdot I_1) - 2 \cdot B_{sat} \cdot z \cdot I_1}}{2 \cdot x} + A \right)^2 + A \cdot B_{sat} \cdot l_p / \mu_0} \\ L_2 = \dfrac{w_S \cdot z^2 \cdot S_{Fe} \cdot B_{sat} \cdot A}{l_{Fe} \cdot \left(\dfrac{z \cdot I_2 - B_{sat} - A \cdot x + \sqrt{B_{sat}^2 + z^2 \cdot I_2^2 + A^2 \cdot x^2 + 2 \cdot A \cdot x \cdot (B_{sat} + z \cdot I_2) - 2 \cdot B_{sat} \cdot z \cdot I_2}}{2 \cdot x} + A \right)^2 + A \cdot B_{sat} \cdot l_p / \mu_0} \\ L_3 = \dfrac{w_S \cdot z^2 \cdot S_{Fe} \cdot B_{sat} \cdot A}{l_{Fe} \cdot \left(\dfrac{z \cdot I_3 - B_{sat} - A \cdot x + \sqrt{B_{sat}^2 + z^2 \cdot I_3^2 + A^2 \cdot x^2 + 2 \cdot A \cdot x \cdot (B_{sat} + z \cdot I_3) - 2 \cdot B_{sat} \cdot z \cdot I_3}}{2 \cdot x} + A \right)^2 + A \cdot B_{sat} \cdot l_p / \mu_0} \end{cases} \tag{17}$$

Where $x = \mu_0 \cdot l_p \cdot (l_{Fe} + l_p)$.

In order to determine the value of the temperature coefficient α_T, it is necessary to measure the dependence of *L (i)* for the temperature $T_1 > T_0$, and then to determine the value of the parameter A_1 at temperature T_1 using the formula (17). The value of α_T is given by:

$$\alpha_T = \frac{T_0 - T_R}{\ln(A_1/A_0)} \tag{18}$$

In order to determine the parameters describing losses in the core:

1. one should read from the catalog characteristics of the core material describing the dependence of power losses density P_v on the amplitude of the magnetic flux density (B_m) at constants frequency *f*, the coordinates of two points $X_4(B_{m1}, P_{V1})$ and X_5 (B_{m2}, P_{V2}). The typical course of such characteristics is shown in Figure 4. Next, one should calculate the value of the *β* coefficient by the formula:

$$\beta = \frac{\log(P_{v1}/P_{v2})}{\log(B_{m1}/B_{m2})} \tag{19}$$

2. to determine the coefficient *α* one should read from the catalog characteristics describing the dependence of the power density of the core loss on frequency (Fig. 4b) at the known amplitude B_m in points $X_6(f_1, P_{V3})$ and $X_7(f_2, P_{V4})$ and calculate the value of the factor α from the formula:

$$\alpha = \frac{\log(P_{v3}/P_{v4})}{\log(f_1/f_2)} \tag{20}$$

3. to determine the parameter P_{V0} it is necessary to read point e.g. $X_6(f_1, P_{V3})$ from the characteristics describing the dependence of power density losses P_V on frequency at the constant value of B_m (Fig. 4b) and next, calculate the value of P_{V0} from:

$$P_{VO} = \frac{P_{v3}}{f_1^{\alpha} \cdot B_m^{\beta} \cdot (2 \cdot \pi)^{\alpha} \cdot [0.6336 - 0.1892 \cdot \ln(\alpha)]} \tag{21}$$

4. in the catalog characteristics $P_v(T)$ at first one should read the value of temperature T_m at which the characteristics of $P_v(T)$ reaches the minimum at point $X_8(T_m, P_{V5})$ (Fig. 4c), then one should select point $X_9(T_6, P_{V6})$ of some characteristics and calculate the parameter *D* by the formula:

$$D = \frac{Pv_6 - Pv_5}{Pv_5 \cdot (T_6 - T_m)^2} \tag{22}$$

In turn, the value of the parameter f_b associated with the dependence defining the output voltage of the controlled voltage source E_{LS} can be determined from the dependence describing the characteristics of the magnetic permeability *μ* of the core of the frequency *μ(f)*, whose typical course is shown in Figure 5.

The frequency f_b is calculated by the formula

$$f_b = \frac{f_1 \cdot \mu_1 - f_2 \cdot \mu_2}{\mu_2 - \mu_1} \tag{23}$$

where in the calculations the coordinates of two points X_{10} (f_1, μ_1) and X_{11} (f_2, μ_2) lying on the curve μ*(f)* were used.

To the electrical parameters appearing in the description of the electrothermal model of the inductor belong

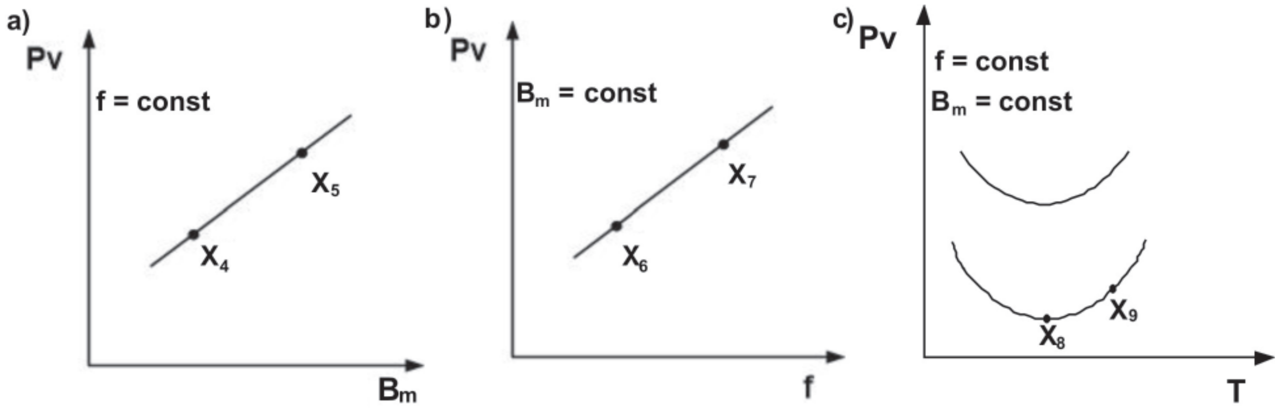


Figure 4: Dependences of power losses density on the amplitude of the flux density (a), frequency (b) and temperature (c)

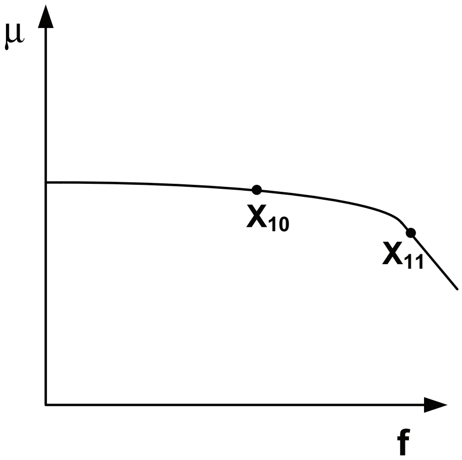


Figure 5: Typical dependence of magnetic permeability of the ferromagnetic core on frequency

also length of the winding l_d and cross-section of the coil wire S_d. These parameters are used to determine series resistance of the coil. The length of the winding for the ring core is estimated by calculating the product of the number of turns z and the girth of cross-section of the core, assuming that it is rectangular, by the formula:

$$l_d = 2 \cdot z \cdot \left(h_R + \left(\left(d_z - d_w\right)/2\right)\right) \tag{24}$$

In turn, the cross-sectional area of the wire is calculated on the basis of simple geometric formulas and the known wire diameter d_3.

The capacitor C_w is determined by the formula:

$$C_w = \left(f_r^2 \cdot 4 \cdot \pi^2 \cdot L_0\right)^{-1} \tag{25}$$

where f_r is resonant frequency of the inductor, L_0 is the inductance value for $I_{DC} = 0$. The resonant frequency of the chocking - coil can be read from the course of the dependence of the impedance module, whose typical course is shown in Figure 6, on frequency.

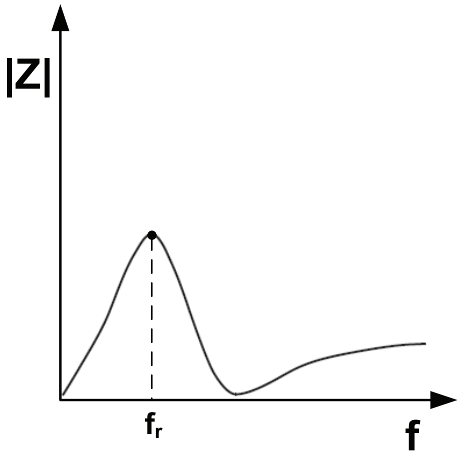


Figure 6: Typical dependence of the module of inductor impedance on frequency

To determine the thermal parameters a_i, τ_{thi}, R_{thi} it is necessary to perform measurements of their own transient thermal impedance of the winding $Z_{thu}(t)$ and of the core $Z_{thr}(t)$, as well as the mutual transient thermal impedance between the core and the winding $Z_{thur}(t)$ using the method described in [28]. Based on the measured waveforms $Z_{thu}(t)$, $Z_{thr}(t)$ and $Z_{thur}(t)$ the values of capacitance and thermal resistance are calculated using the method described in [22, 23].

4 Experimental results

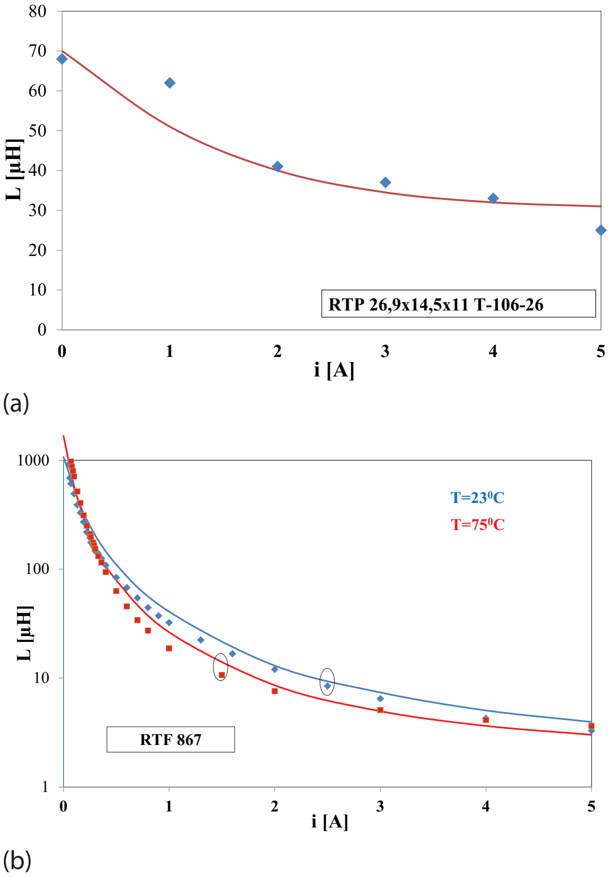
In order to verify the correctness of the proposed method of estimating parameters of the inductor, the values of the parameters of two arbitrarily selected inductors with ferromagnetic cores were estimated and the calculated and measured characteristics of these inductors were compared. The investigations were performed for two inductors containing ring cores of the same size (26.9 mm x 14.5 mm x 11 mm). The first one was the core RTF of ferrite material F-867 and the other was the core RTP of powdered iron from the material T106 -26. On both the cores 20 turns of the enameled copper wire of 0.8 mm diameter were wound. Using the estimation algorithm proposed in the previous section, the values of all the model parameter values were read or calculated and collected in Table 1.

The measured and calculated characteristics of the considered inductors are shown in Figures 7 – 8. In these figures the results of measurements are denoted as points, whereas the results of electrothermal analysis are represented by lines.

Table 1: Values of parameters of the electrothermal model of inductors with the cores RTP T106-26 and RTF F 867.

Parameter	B_{sat0} [T]	l_p [μm]	T_C [K]	A [A/m]	α_{BS} [1/K]
RTP T106-26	1.38	14	1023	4024	$2.8 \cdot 10^{-3}$
RTF F867	0.5	0.1	488	260	$2.8 \cdot 10^{-3}$
Parameter	ws	l_{Fe} [mm]	V_e [m^3]	S_{Fe} [m^2]	z
RTP T106-26	0.5	64.99	$4.43 \cdot 10^{-6}$	$68.2 \cdot 10^{-6}$	20
RTF F867	0.5	62.8	$3.14 \cdot 10^{-6}$	$50 \cdot 10^{-6}$	20
Parameter	S_d [m^2]	l_d [m]	P_{v0} [kW/m^3]	D [K^{-2}]	α
RTP T106-26	$502 \cdot 10^{-9}$	0.6	2	0	1.59
RTF F867	$502 \cdot 10^{-9}$	0.6	100	$0.5 \cdot 10^{-6}$	1.02
Parameter	β	α_T [1/K]	T_m [K]	f_b [kHz]	d [mm]
RTP T106-26	2.15	$100 \cdot 10^3$	368	546	0.8
RTF F867	2.82	240	343	850	0.8

Figure 7 shows the dependence of inductance on the DC current of the inductor containing the powder core RTP T106 -26 (Fig. 7a) and the inductor with the ferrite core RTF F867 (Fig.7b) The tests were performed at frequency of 100 kHz for two ambient temperatures equal to 23 and 75°C. As you can see, good agreement between the results of measurements and calculations was obtained. For both the considered choking–coil the dependence *L(i)* is a decreasing function of the current, where the choking–coil with the ferrite core with the same geometrical dimensions achieved a higher value of inductance, moreover a wider range of changes in its value was observed. A decrease in inductance of the ferrite core (even two hundreds times) was much larger than for the core of the powdered iron (about 30 %). The different courses of the dependence *L(i)* for both the inductors were due to the non-linear magnetization curve of ferromagnetic cores. It is worth noticing that the course of the dependence *L(i)* for the choking–coil with the ferrite core showed the visible influence of the ambient temperature on its course, while for the inductor with the powder core such influence is not observed. In the characteristics of the choking–coil with the ferrite core an increase in temperature equal to 50 °C caused an increase in its inductance even up to 45 %.



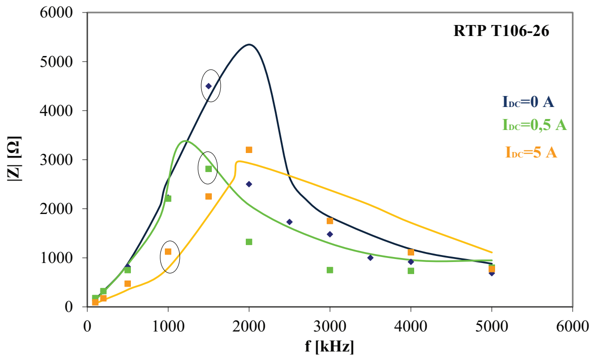
(a)

(b)

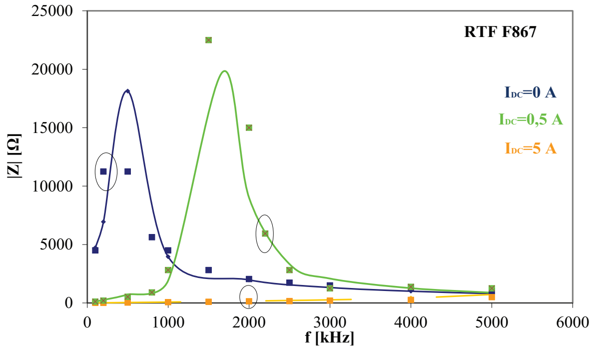
Figure 7: Measured and calculated dependence of inductance of inductors with the powder (a) and ferrite (b) cores on the current

Figure 8 shows the dependences of the module of impedance of the choking–coils with the considered cores on frequency at the constant values of the DC current. As it is visible, good agreement between the measurements and calculations results was obtained. By considering winding capacitance in the electrothermal model of the choking–coil the resonance on these characteristics was obtained, which corresponds to the obtained measurement results. The value of the resonant frequency for the ferrite core increases with an increase of the DC current, whereas for the powder core it oscillates in the range of 1.3 MHz to about 2.3 MHz.

In order to illustrate the influence of the nonlinearity of the inductor and the self-heating phenomena in this element on characteristics of dc-dc converters, the results of calculations (lines) and measurement (points) of the boost converter with the core RTP T106-26 [29] were presented in Figs. 9 and 10. In Fig.9 calculated and measured dependences of the output voltage V_{out}



(a)



(b)

Figure 8: Calculated and measured dependences of the module of impedance of inductors with the powder (a) and ferrite (b) cores on frequency

of the examined converter on the load resistance R_0 at the fixed value of the duty factor of the control signal d = 0.5 at two values of the frequency of the control signal equal in turn 50 kHz and 400 kHz, are presented. Results of calculations passed with the use of the electrothermal model of the inductor are marked with solid lines, whereas results of calculations obtained by means of the linear model of the inductor are marked with dashed lines.

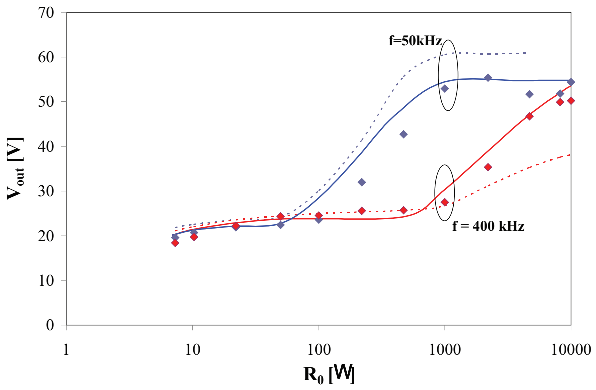


Figure 9: Calculated and measured dependences of the output voltage of the boost converter on the load resistance

As one can notice, the use of the electrothermal model of the inductor makes possible to obtain the considerably better agreement between performance of calculations and measurement than with the use of the linear model of the inductor. It is proper to notice that the regard of losses in the inductor and dependences of the inductances on frequency causes a decreasing in the output voltage of the considered converter. The use of the linear model of the inductor can cause the overestimate of results of calculations even about 50%.

In turn, Fig.10 illustrates the dependence of the core temperature T_R (solid lines) and the winding temperature T_U (dashed lines) on the load resistance corresponding to characteristics from Fig.9. As it is visible, for both considered frequencies the decreasing dependences $T_R(R_0)$ and $T_U(R_0)$ are obtained, whereas an increase in frequency causes a decrease in value of the temperature of the inductor. From the fact, that the winding temperature is lower than the core temperature results, that a main source of losses is the core of the inductor.

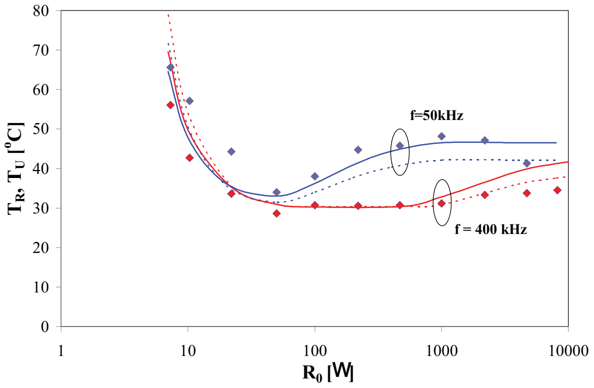


Figure 10: Calculated and measured dependences of the core and winding temperatures of the load resistance

5 Conclusions

This paper describes the electrothermal model of the choking–coil with ferromagnetic the core dedicated for SPICE software and proposes a method of estimating values of magnetic, electrical and thermal parameters of this model. The proposed algorithm is simple to implement and largely uses the data presented by manufacturers of the ferromagnetic core and winding wire in the catalog data.

The investigations were performed for two arbitrarily chosen inductors with the core made of powdered iron and ferrite material. The presented experimental results show that the proposed method of estimating the parameters is correct, which is proved by good agreement between the measured and calculated characteristics of the considered inductors.

The electrothermal model of the inductor together with the proposed estimation method of its parameters can be useful for designers of switch-mode power supplies and in the analysis of the considered class of electronic circuits.

6 Acknowledgements

This project is financed from the funds of National Science Centre which were awarded on the basis of the decision number DEC-2011/01/B/ST7/06738.

7 References

1. Rashid M.H.: "*Power Electronic Handbook*", Academic Press, Elsevier, 2007.
2. Ericson R, Maksimowic D.: "*Fundamentals of Power Electronics*", Norwell, Kluwer Academic Publisher, 2001.
3. Barlik R., Nowak M.: *„Energoelektronika – elementy, podzespoły, układy"*. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2014.
4. Górecki K., Stepowicz W.J.: "*Comparison of Inductor Models Used in Analysis of the Buck and Boost Converters*". Informacije MIDEM, Vol. 38, No.1, 2008, pp. 20-25.
5. Van den Bossche A., Valchev V.C.: "*Inductors and transformers for Power Electronics*". CRC Press, Taylor & Francis Group Boca Raton, 2005.
6. Górecki K., Detka K.: "*Electrothermal model of choking-coils for the analysis of dc-dc converters*". Materials Science & Engineering B, Vol. 177, No. 15, 2012, pp. 1248-1253.
7. Wac-Włodarczyk A.: *„Materiały magnetyczne. Modelowanie i zastosowania"*. Monografie – Politechnika Lubelska, 2012
8. Górecki K., Detka K.: "*Investigations of temperature influence on the properties of the choking-coils with selected ferromagnetic cores*". Microelectronic Materials and Technologies, Vol. 2, Koszalin, 2012, pp. 180-191
9. Borkowski A.: *„Zasilanie urządzeń elektronicznych"*, WKiŁ, Warszawa 1990.
10. Górecki K., Detka K.: "*The electrothermal model of choking – coil for SPICE*", Elektronika – konstrukcje, technologie, zastosowania, No. 1, 2014, pp. 9 - 11.
11. Górecki K., Rogalska M., Zarębski J., Detka K.: "*Modelling characteristics of ferromagnetic cores with the influence of temperature*". Journal of Physics: Conference Series, Vol. 494, 2014, 012016, doi:10.1088/1742-6596/494/1/012016
12. Górecki K., Zarębski J.: "*Modeling Nonisothermal Characteristics of Switch-Mode Voltage Regulators*". IEEE Transactions on Power Electronics, Vol. 23, No. 4, 2008, pp. 1848 – 1858.
13. Wilson P.R., Ross J. N., Brown A. D.: "*Simulation of magnetics components models in electrics circuits including dynamic thermal effects*", IEEE Trans. on Power Electr., Vol.17, 2002, No 1, pp. 55 – 65
14. Maksimovic D., Stankovic A. M., Thottuvelil V. J., Verghese G. C.: "*Modeling and simulation of power electronics converters*", Proceedings of the IEEE, Vol. 89, No. 6, 2001, pp. 75 – 84.
15. Mohan N., Robbins W.P., Undeland T. M., Nilssen R., Mo O.: "*Simultion of Power Electronics and Motion Control Systems – An Overview*", Proceedings of the IEEE, Vol. 82, 1994, pp. 1287 – 1302.
16. Zarębski J., Górecki K.: "*Modelling CoolMOS Transistors in SPICE*". IEE Proceedings on Cicuits, Devices and Systems, Vol. 153, No. 1, 2006, pp. 46-52.
17. Basso C.: "*Switch – Mode Power Supply SPICE Cookbook*", McGraw – Hill, New York, 2001.
18. Górecki K., Zarębski J.: "*Electrothermal analysis of the self-excited push-pull dc-dc converter*". Microelectronics Reliability, Vol. 49, No.4, 2009, pp. 424-430.
19. Górecki K., Stepowicz W.J.: *„Wpływ zjawiska samonagrzewania w dławiku na charakterystyki przetwornicy buck"*. Przegląd Elektrotechniczny, Vol. 85, No. 11, 2009, pp. 145-148.
20. K. Chwastek: "*Frequency behaviour of the modified Jiles – Atherton model*", Physica B, Vol. 403, 2008, pp. 2484-2487.
21. Wilamowski B.M., Jaeger R.C., "*Computerized circuit Analysis Using SPICE Programs*", McGraw-Hill, New York 1997.
22. Górecki K., Rogalska M., Zarębski J.: "*Parameter estimation of the electrothermal model of the ferromagnetic core*", Microelectronics Reliability , Vol. 54, No. 5, 2014, pp. 978 – 984.
23. Górecki K., Rogalska M.: "*The Compact Thermal Model of the Pulse Transformer*". Microelectronics Journal, Vol. 45, No. 12, 2014, pp. 1795-1799.
24. Zarębski J., Górecki K.: "*Parameters Estimation of the D.C. Electrothermal Model of the Bipolar Transistor*". International Journal of Numerical Modelling Electronic Networks, Devices and Fields. Vol. 15, No. 2, 2002, pp. 181-194.
25. *Arnold Magnetics Limited Powder Cores* – catalogue data, www.arnoldmagnetics.com
26. *Web-page of Feryster* http://www.feryster.com.pl/polski/kat10.php
27. Górecki K., Detka K., Zarębski J.: *„Pomiary wybranych parametrów i charakterystyk materiałów i ele-*

mentów magnetycznych". Elektronika, No. 1, 2013, pp. 18-22

28. Górecki K., Górecka K., Detka K.: *„Pomiary parametrów termicznych dławików"*. Zeszyty Problemowe Maszyny Elektryczne No. 100, 2013, pp. 135-140.
29. Detka K., Górecki K.: *„Wpływ samonagrzewania w dławiku na charakterystyki przetwornicy typu boost"*. Przeglad Elektrotechniczny, Vol. 90, No. 9, 2014, pp. 19-21.

Arrived: 06. 06. 2014
Accepted: 28. 10. 2014